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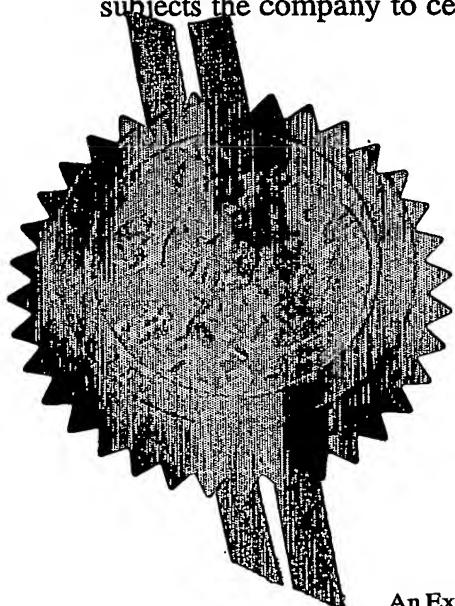
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ACOUSTIC EMISSION PARAMETERS BASED ON INTER-ARRIVAL TIMES OF ACOUSTIC EMISSION EVENTS

5. Name of your agent (if you have one)

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TECHNOLOGY COMMERCIALISATION MANAGER
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Bearing condition monitoring using a Shape-to-Life (STL) ratio of inter-arrival time distribution of acoustic emission events

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Abstract

The novel Shape-to-Life (STL) method is based on the detection of inter-arrival times of successive AE events[†]. These inter-arrival times follow a Weibull distribution. The method provides two parameters, STL and L_{63} , that are derived from the estimated Weibull parameters of the distribution's shape (γ), characteristic life (θ) and guaranteed life (t_0). It is found that STL and L_{63} are related hyperbolically. In addition, the STL value is found to be sensitive to bearing wear, the load applied to the bearing and the bearing rotating speed. Of the three influencing factors, bearing wear has the strongest influence on STL and L_{63} . For the proposed machine condition monitoring system to work, the effects of load and speed on STL need to be compensated, as discussed in the paper.

1. Introduction

Rolling element bearings are omnipresent in almost all kinds of rotating machines. Condition monitoring of bearings has attracted considerable interest for many years because a majority of problems in rotating machines are caused by faulty bearings. A reliable condition monitoring system will significantly reduce failure and unplanned maintenance, and hence the huge attendant cost due to machine downtime. Often the system is used with an operator who assists in the interpretation of the machine signals for early failure detection and fault diagnosis.

Nowadays there are two kinds of methods available for bearing maintenance: statistical bearing life estimation, and bearing condition monitoring and diagnostics. Statistical bearing life estimation predicts the fatigue life of a bearing [1]. However, its application has many limitations, since unusual operating conditions can severely decrease a bearing's life. In these cases, bearing life estimates become unreliable leading to unexpected breakdown. On the other hand, bearing condition and diagnostics can be a very reliable method because it gives up-to-date information about the condition of a bearing. The most popular approaches for bearing condition monitoring are vibration and acoustic emission (AE) analyses.

It has been shown that vibration methods are effective only at high rotating speeds when the intensity of excitation is large, whereas AE methods are preferred for lower-speed operations. Acoustic emission is a natural phenomenon of sound generation applied to

* Contact person

[†] Patent application pending

the spontaneously generated elastic wave produced within a material under stress. Plastic deformation and growth cracks are the primary sources of AE in metals. The acoustic signal can be detected by a piezoelectric sensor which converts the mechanical energy carried by the elastic wave into an electrical signal. In the case of a rotating element bearing, when a defective roller surface comes into contact with other elements, it produces AE events because of the shock impulses leading to a release of strain energy.

2. Inter-arrival times

An AE signal consisting of seven AE events is shown in Figure 1. Dedicated AE measuring instruments – for example, the AET5500 – capture each event that goes above a predefined threshold and extract various AE parameters together with a time stamp of the event. The time difference between two consecutive AE events is called the inter-arrival time between them. A high-speed data acquisition system – for example, the LABVIEW on PC – captures the whole time signal (Figure 1) from which the inter-arrival times are extracted.

The collection of inter-arrival times forms a distribution, which, as is proven in the next section, is a Weibull distribution used in reliability studies to model time to failure. In this context, the occurrence of an AE event can be regarded as an instance of failure on a microscopic scale.

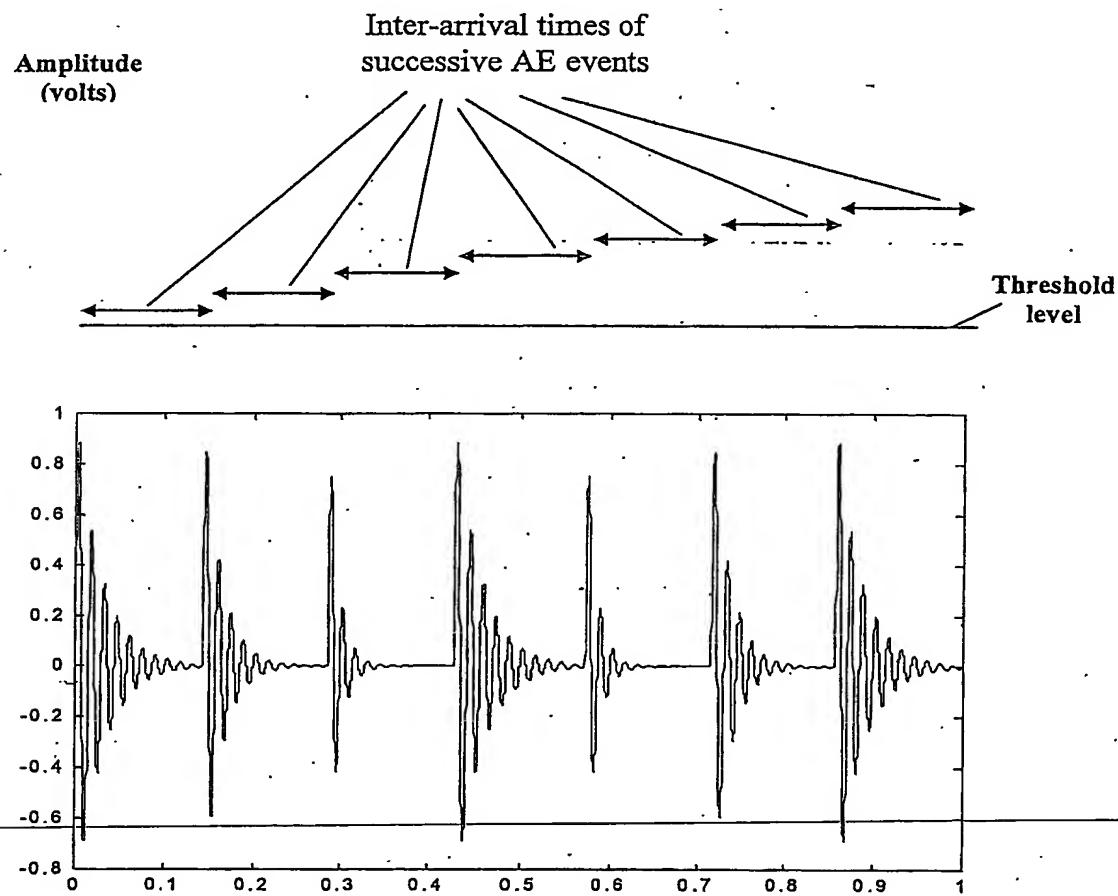


Figure 1 Inter-arrival times of successive AE events

3. Theory

The Weibull distribution has been used in reliability engineering to model times to failure [2]. Its usefulness lies in the simplicity that a single probability density function can be made to represent the time-of-failure arising from different modes of failure (running-in, random and wear-out). Since an instance of AE can be considered a kind of failure on a microscopic scale, the Weibull distribution is most likely to be suitable also for representing the probability of inter-arrival of AE events at a sensor. In this sense, the inter-arrival time is equivalent to time-to-failure. The justification for using the Weibull distribution is set out in this section.

The cumulative probability, $F(t)$, of inter-arrival times of AE events must, by virtue of its definition, increase monotonically with the time interval t , starting with a probability value of zero at time $t = 0$ and approaching unity as time t tends to infinity. The form of this curve, known as the cumulative probability curve, for mathematical convenience, is represented by an exponential function as

$$F(t) = 1 - e^{-\phi(t)} \quad \text{Equation 1}$$

Equation 1 is graphed in Figure 2, where it can be seen that $\phi(t)$, a function of time t , determines the precise form of the curve.

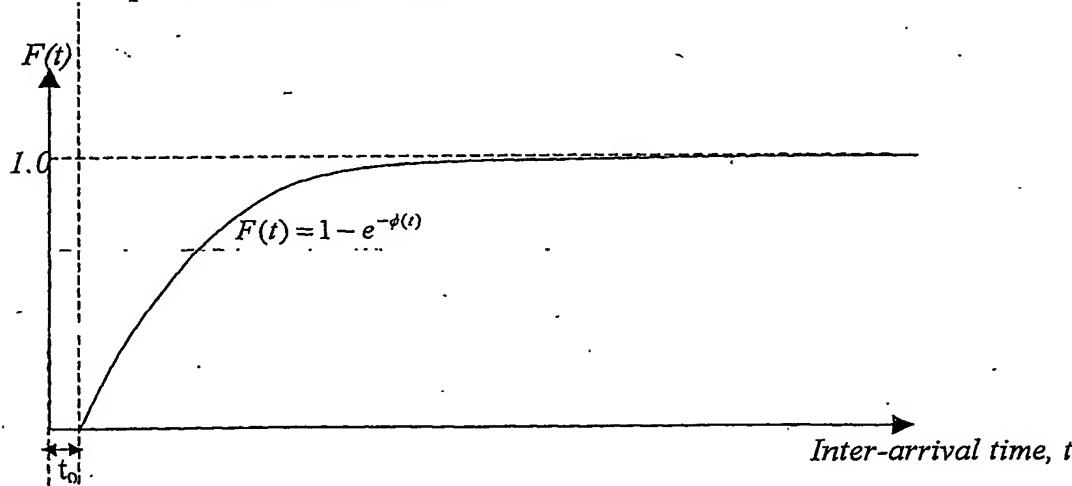


Figure 2 Cumulative probability of inter-arrival time $F(t)$

When an AE event occurs, it occupies a finite time interval during which the occurrence of yet another event cannot be distinguished with an AE measuring instrument. Therefore, the inter-arrival time that can be measured of the subsequent AE must not be shorter than the event duration of the current one. In effect, this means that a subsequent detectable event cannot occur in a time less than the event duration of the current one. In the context of cumulative probability $F(t)$, its value has to be zero below some threshold time t_0 , known as the guaranteed life.

The function $\phi(t)$, which defines the precise form of the cumulative probability $F(t)$, should be non-dimensional because it is an exponent of the constant e in Equation 1.

Taking account all of the foregoing considerations, it is reasonable to suggest that $\phi(t)$ take the form

$$\phi(t) = \left(\frac{t - t_o}{\theta} \right)^\gamma ,$$

where t_o = the guaranteed life
 θ = the characteristic life, and
 γ = the shape parameter.

Thus, the inter-arrival times have the cumulative distribution function (cdf) given by

$$F(t) = 1 - e^{-\left(\frac{t - t_o}{\theta} \right)^\gamma} \quad \text{for } t \geq t_o , \quad \text{Equation 2}$$

and the corresponding probability density function (pdf) of form

$$f(t) = \frac{\gamma \cdot (t - t_o)^{\gamma-1}}{\theta^\gamma} \cdot e^{-\left(\frac{t - t_o}{\theta} \right)^\gamma} \quad \text{for } t \geq t_o . \quad \text{Equation 3}$$

It is noted that Equations 2 and 3 are indeed the respective cdf and pdf of the Weibull distribution. In these equations $(t - t_o)$ denotes the 'quiet' zone, which marks the period after one AE event has dropped below the threshold and before the occurrence of the next.

The parameter θ is referred to as the characteristic life in the Weibull distribution when used to describe the probability of time-to-failure in reliability work. This term is appropriate if, as mentioned before, an AE occurrence is regarded as a microscopic failure, which has been accepted to be the case. Characteristic life is therefore the characteristic AE inter-arrival time in this context. If the quiet zone $(t - t_o)$ is as long as the characteristic life θ , then at the inter-arrival time of $t = t_o + \theta$, the cumulative probability has the value of

$$F(t_o + \theta) = 1 - e^{(-1)} = 0.63$$

In other words, if a hundred inter-arrival times were collected, 63 would have a value less than $t_o + \theta$.

The shape factor, γ , in Equations 2 and 3 is used to express the various patterns of the inter-arrival time distribution, some of which are shown in Figure 3. For $\gamma = 1$, $f(t)$ becomes an exponential probability density function. When $\gamma = 2$, the density function is known as a Rayleigh distribution. When $\gamma = 3.43$, the density function becomes a Normal distribution function.

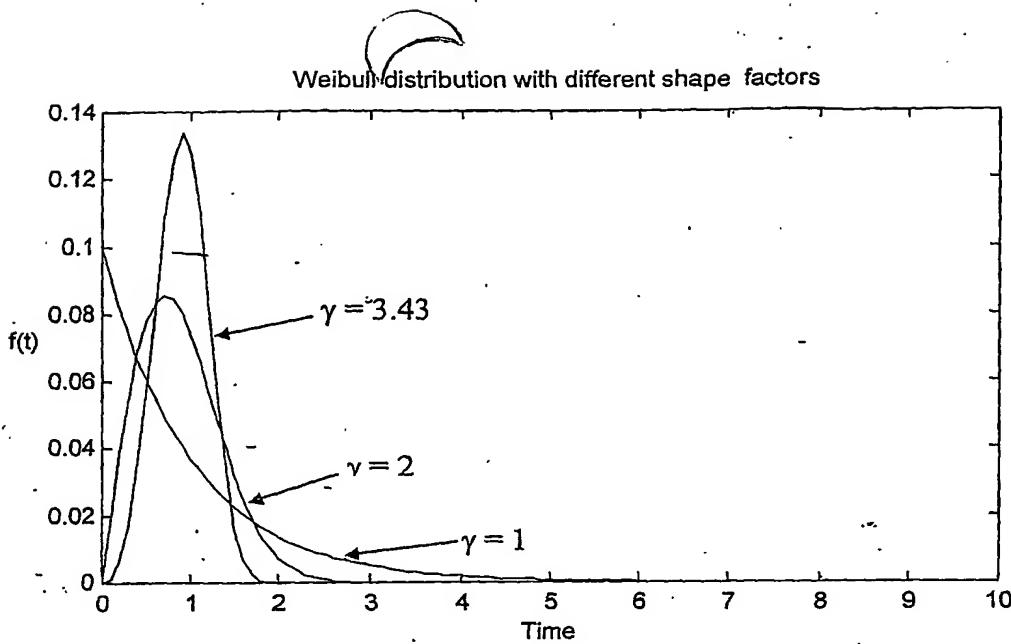


Figure 3 Weibull distribution with different shape factors

4. Definition of STL and L_{63}

Once a collection of inter-arrival times of an AE signal is formed, a Weibull distribution is then fitted to it and the Weibull parameters, shape (γ) and characteristic life (θ) and guaranteed life (t_0), can be estimated. Note that γ , being the exponent in Equation 1, is non-dimensional; θ and t_0 have the dimension of time and hence the unit seconds.

The STL is defined to be the ratio of shape to characteristic life [3]. In symbols, it is

$$STL = \frac{\gamma}{\theta} \quad \text{Equation 4}$$

It is obvious that STL has the unit of s^{-1} .

L_{63} denotes the time duration within which 63% of the inter-arrival times of the distribution lies. The L_{63} duration [3] has a value,

$$L_{63} = t_0 + \theta. \quad \text{Equation 5}$$

5. Experimental validation

A test rig was designed intended for different loading conditions and built in order to evaluate the proposed monitoring scheme. From now on this test rig will be referred to as the low-speed heavy-duty test rig. The test rig was used in this research to study the effect of variation of loading conditions on AE and vibration at slow rotating speed. The original rig was later modified such that a radial load can be applied to the rotating shaft using hydraulics and the speed of the shaft can be lowered still further using an inverter and motor controller. A sketch of the low-speed heavy-duty test rig is shown in Figure 4.

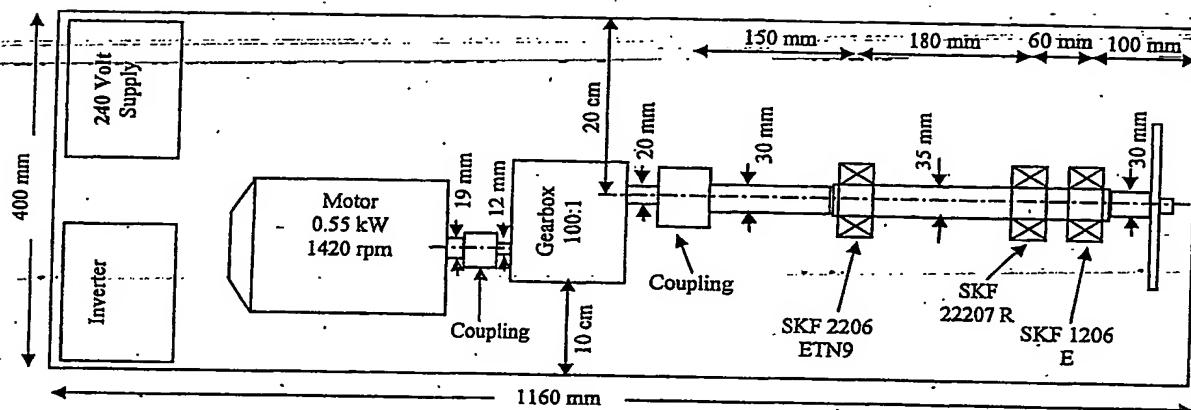


Figure 4 Sketch of the test low-speed heavy duty rig

The design of the test rig comprises a rotating shaft supported at three points: a double-row self-aligned ball bearing at the drive end, a spherical roller bearing at the applied load position near the non-drive end and a single row self-aligned ball bearing at the non-drive end. The shaft of 35 mm diameter is manufactured in steel. The three bearings are a SKF 22207 E which is a double-row self-aligned ball bearing, a SKF 22207 R which is a spherical roller bearing and a SKF 1206 E which is a single row self-aligned ball bearing. They are mounted in bearing housings that in turn are attached to a base plate.

The low-speed heavy-duty test rig was run at 0.23 rev/sec. The bearing under test was an SKF 1206E, which is a self-aligned ball bearing with a maximum load capacity of about 137 bars. AE signals were captured using a WD (wideband) transducer mounted on the top of the non-drive end bearing housing. These signals were amplified with a 60 dB gain and filtered with a 100 kHz – 450 kHz band-pass filter. The sampling rate was 1 MHz.

Measurements started with no radial load applied to the test bearing and the load was then increased at 50-bar steps up to 300 bars. From the loads of 0 to 250 bar, each loading condition were maintained for about 2 hours, thus taking about 12 hours to reach the end of the 250-bar test. Then the load was increased to 300 bars and maintained until the test bearing failed.

6. Results and discussion

Figure 5 suggests that the STL values increased when the bearing was overloaded, and with the load maintained indefinitely (300 bar load from the 12th to the 120th hour), the STL increased with progressive bearing wear until the final failure. At the 300 bar load, the STL started with a value of 18.9 and increased monotonically to 59.4 when it failed, representing just over a three-fold increase.

Figure 6 shows a graph of the STL against L_{63} for all four levels of load applied sequentially to the bearing during the accelerated life test. The hyperbolic relationship between STL and L_{63} is demonstrated in Figure 6.

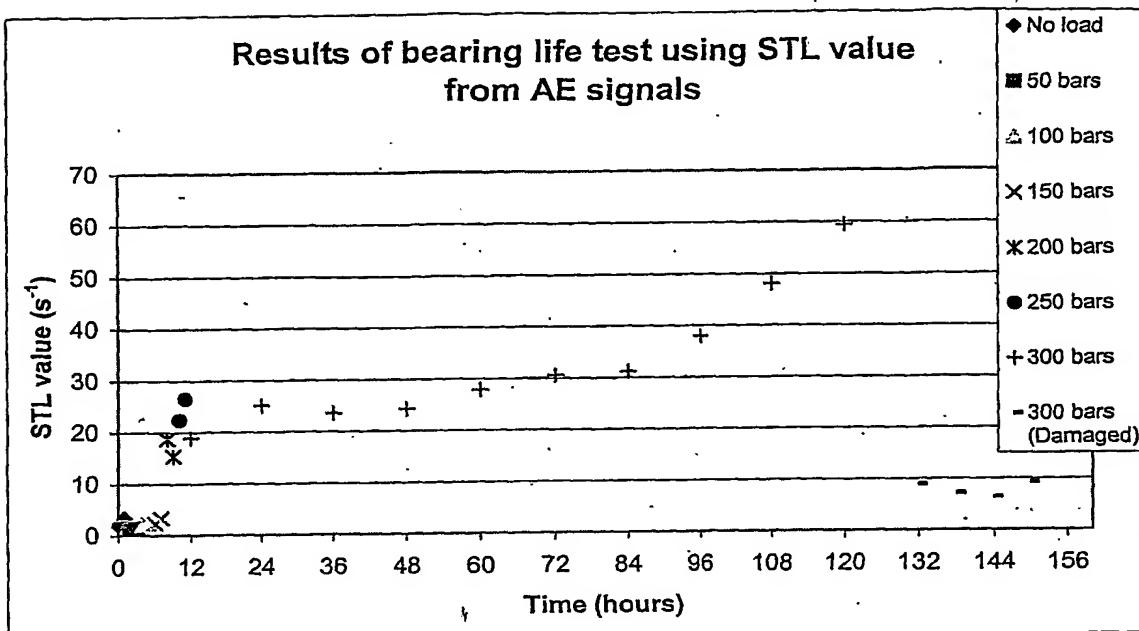


Figure 5 Progression of STL with time from bearing life test

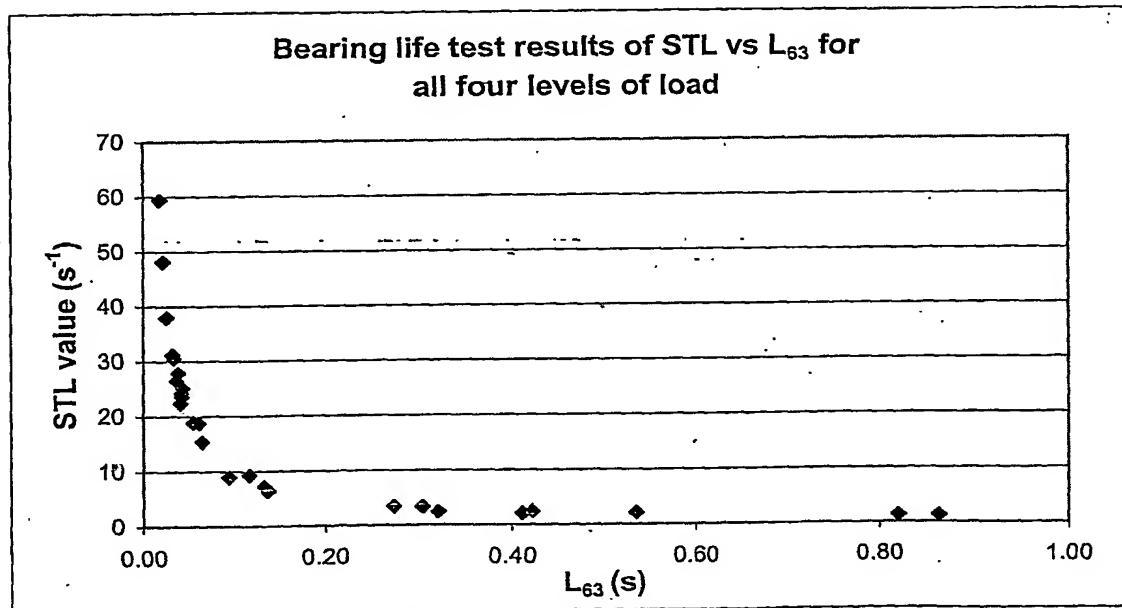


Figure 6 STL versus L_{63} from the bearing life test

It has been observed that bearing loading below the bearing's load carrying capacity produces a rather small STL value, typically not more than 8 s^{-1} . The test bearing has a load carrying capacity of 137 bars. This low value of 8 s^{-1} , compared to the range of increase in STL of $(59-19) = 40 \text{ s}^{-1}$ due to the effect of bearing wear alone for the bearing subjected to a constant load of 300 bars (Figure 6), is only a fifth.

It therefore seems to suggest that lower bearing loading makes the STL value even more sensitive to bearing wear. In summary, bearing wear exerts a much stronger influence on STL than does the load as long as the latter is kept below the bearing's recommended load carrying capacity. Condition monitoring of the main bearing on the British Airways London Eye using the STL method has been under investigation [4][5].

7. Conclusions

The STL and L_{63} values have been explored in this project and demonstrated as sensitive condition monitoring AE parameters. The STL method is based on the modelling of inter-arrival times of AE events with Weibull distribution. The STL is defined as the ratio of two estimated Weibull parameters, shape to characteristic life (Equation 4). The L_{63} is defined as the summation of the estimated guaranteed life and characteristic life (Equation 5). Both the STL and L_{63} values are influenced by wear, speed and loading.

Effect of load on STL

From the experiments, it has been found that the STL values remain more or less level if the bearing is subjected to the applied load within basic dynamic load rating. When the applied load becomes greater, the STL is increased whilst the L_{63} is decreased.

Effect of speed on STL

The change in speed of rotating machines has been found to affect the STL values. This is because the rotating speeds and inter-arrival times are approximately inversely related. The effect of speed variations on STL can be compensated using the hyperbolic relationship between STL and L_{63} .

Effect of wear on STL

Similar to load and speed, STL has been found to be influenced by wear. From the progressive bearing wear test, it is clear that the progression of wear results in a monotonically increasing trend of STL. When the bearing failed to operate, the STL was increased to about 30 times the value for the initial bearing condition (Figure 5). In order to set the threshold for STL as a bearing condition alert, the choice of threshold level is governed by the rule that the alarm level should be set no higher than five times the initial STL value of the bearing.

Hyperbolic relationship between STL and L_{63}

It has been found that the rotating speed and inter-arrival time between AE events are inversely proportional to each other, resulting in the hyperbolic relationship between STL and L_{63} . This hyperbolic curve provides the basis for adjusting STL and L_{63} for speed compensation and load compensation.

8. Acknowledgements

The first author gratefully acknowledge the support of the Royal Thai government and the Department of Physics, Faculty of Science, Chulalongkorn University in awarding a Ph.D. scholarship. The authors also wish to thank Corus, Middlesborough UK, which has kindly provided advice and equipment for experimentation, the support of EPSRC (Grant GR/M44200) and the nine industrial collaborators including the UK National Physical Laboratory within the INTERSECT Faraday Partnership Flagship Project (1998-2002) entitled "Acoustic Emission Traceable Sensing and Signature Diagnostics (AESAD)" (Project website: <http://www.brunel.ac.uk/research/bcmm/aesad/>).

9. References

- [1] Kaewkongka T., Au Y. H. J. (2001) Application of acoustic emission to condition monitoring of rolling element bearings. *Journal of Measurement and Control*. 34 245-247.
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- [3] Kaewkongka T. (2002) *Bearing Condition Monitoring using Acoustic Emission and Vibration – The Systems Approach*. PhD Thesis, Brunel University.
- [4] Harris A J (2002): Investigation in Using Acoustic Emission to Monitor the Condition of the Main London Eye Bearings. MPhil Thesis, Brunel University.
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BRUNEL UNIVERSITY
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Title: **Acoustic Emission Parameters Based on Inter-Arrival Times of Acoustic Emission Events**

Inventors: **Dr Y H J Au, Professor B E Jones, Dr R T Rakowski and Dr T Kaewkongka**

Claims:

1. A Shape-to-Life (STL) parameter having the unit (per second) based on inter-arrival times of successive Acoustic Emission (AE) events and defined as the ratio of the shape factor of the inter-arrival time distribution to the characteristic and guaranteed life, in the statistical distribution (L63) used to describe probability of time to failure as used in reliability analysis employing the Weibull distribution.
2. An Acoustic Emission (AE) condition monitoring system employing the Shape-to-Life (STL) parameter to determine a trend with time in operational performance of a machine, process or material such as bearing wear of a rotating machine.
3. A condition monitoring system providing an observable output of the Shape-to-Life (STL) parameter as a function of a particular cumulative probability parameter of the total number of inter-arrival times of the Acoustic Emission (AE) events, for example the sum of the characteristic life and guaranteed life of the Weibull distribution (L63).
4. An Acoustic Emission (AE) condition monitoring system employing the Shape-to-Life (STL) parameter and set to provide an output indication when the parameter has changed with time by a particular mount or fraction.

Summary

1. Two parameters, derived from the statistics of a Weibull distribution, are created as a measure of the condition of machines or their constituent parts such as bearings. The distribution is that of the inter-arrival times of acoustic emission (AE) events occurring during the machines in operation. These parameters are named the STL and L_{63} : the former is defined to be the ratio of the shape parameter to the characteristic life of the Weibull distribution whilst the latter the sum of the characteristic life and guaranteed life.
2. Due to the fact that AE sources are numerous and varied in a running machine, the shape parameter is unity approximately. Consequently, the STL versus L_{63} graph depicts a hyperbolic curve. As the condition of a machine element deteriorates, the corresponding point moves up the curve.
3. In the case of bearing condition monitoring, the co-ordinates (STL, L_{63}) of the point are also affected by rotating speed and load on the bearing. However, they can be compensated by a known means based on the result of a simulation study backed up by experimental validation.
4. Although the method is equally applicable for bearings running at high as well as low speeds, its power over the vibration monitoring method lies in its ability to monitor low-speed bearings down to the speed of that of the London Eye, that is, at 2 revolutions per hour.

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